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Timing matters! The neural signature of intuitive judgments differs according to the way information is presented

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ABSTRACT

One can conceive of intuition as the preliminary perception of coherence. Since this requires holistic perception, it is hypothesized that underlying processing strategies are dependent on the possibility to obtain all relevant information at once. The present study used magnetoencephalography (MEG) to investigate neural mechanisms underlying intuitive coherence perception when semantic concepts are presented all together (simultaneously) or one after the other (sequentially). With simultaneous presentation, absolute activation increases in the left OFC when participants recognize coherence. With sequential presentation activation increases in the right OFC when participants conclude that there is no common associate between the words presented. Behavioral performance was similar in the two experiments. These results demonstrate that the way information is revealed over time changes the processing of intuitive coherence perception. We propose that such changes must be taken into account to disentangle the neural and behavioral mechanisms underlying different accounts of intuition and related phenomena.

1. Introduction

In everyday life, we continuously encounter situations in which decisions have to be made immediately, with no time to go through all of the possible alternatives and reasoning steps. Such kinds of decisions have been termed intuitive (e.g., Evans, 2008; Kruglanski & Gigerenzer, 2011; Volz & Zander, 2014). There are many different approaches to conceptualize intuition and no generally agreed on definition exists (e.g., Glöckner & Witteman, 2010). One possible way to conceive of intuitive decisions is in relation to the perception of coherence in the environment: The recognition of an association between stimuli forming a meaningful concept or a Gestalt. As Bowers, Regehr, Balthazard, and Parker (1990) put it, intuition can then be defined as "a preliminary perception of coherence (pattern, meaning structure) that is at first not consciously represented, but which nevertheless guides thought and inquiry toward a hunch or hypothesis about the nature of the coherence in question" (p. 74). This definition allows a clear experimental operationalization of intuitive judgments (e.g., Balas, Sweklej, Pochwatko, & Godlewska, 2012; Bolte, Goschke, & Kuhl, 2003; Bowers et al., 1990) and we therefore suggest it

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as an appropriate starting point to investigate the neural underpinnings of intuitive processing and to approach the question to what extend intuition can be considered a coherent concept on a neural level.

If we investigate intuition in the framework of coherence judgments it is intrinsically linked to a holistic appraisal of the environment (e.g., Pretz, 2011). An intuitive perception of coherence then represents an immediate and novel recombination of knowledge and information precipitated out of memory (Bowers et al., 1990). Thus, in order for coherence to be recognized, relevant information from different mnemonic networks need to be integrated into a global percept. One idea of how this might be achieved draws on the spreading activation theory of semantic processing (Collins & Loftus, 1975). According to this theory, a specific concept's presentation leads to an automatic spread of activation of a network of close as well as remote associates. Intuitive semantic coherence judgments, for example, would then be considered as the partial activation of a common associate between remotely linked semantic concepts. Such a partial activation may already be sufficient to trigger a feeling of coherence, even if the basis of this coherence cannot yet be explained or verbalized. To test this assumption, Bowers et al. (1990) developed a semantic coherence judgment task (Dyads of Triads Task, DTT), in which participants were presented with three words (a triad) and had to judge (1) whether they believed those words to be semantically related (a coherent triad) and (2) whether they could name the common associate that related the triad's constituents. Indeed, experiments from Bowers et al. as well as others have repeatedly shown that people are able to make judgments on semantic coherence with a significant over-chance accuracy even if they are not able to name the common associate (e.g., Balas et al., 2012; Bolte et al., 2003; Bowers et al., 1990; Ilg et al., 2007; Topolinski & Strack, 2009). This finding argues for the idea that a feeling of coherence in semantic judgments – whether or not the basis of this feeling can already be verbalized – is actually indicative of intuitive mechanisms, in the sense of a preliminary and implicit recognition of coherence.

In comparison with the increasing number of behavioral studies on intuitive coherence judgments, there is relatively little research investigating their neural underpinnings. Such studies are, however, crucial for a more specific definition of intuition in the framework of coherence detection by gaining a deeper understanding of the underlying neural mechanisms. In the semantic domain, Ilg et al. (2007) applied functional magnetic resonance imaging (fMRI) while participants were working on a coherence judgment task similar to Bowers and colleagues' DTT. In tasks involving the implicit recognition of coherence in a word triad, they found an increased activation of regions of the brain related to semantic processing as well as in regions of heteromodal association areas (superior temporal sulcus and inferior parietal lobule). On the basis of their results, they argue for a conceptualization of intuition that conforms to the spreading activation theory, namely that an intuitive feeling of coherence results from the activation of remotely linked semantic concepts that does not yet lead to full conscious retrieval. It remains to be investigated which mechanisms allow for the integration of such remotely associated concepts from distinct semantic networks.

A brain region that may be intrinsically related to an initial integration of partially retrieved concepts is the orbitofrontal cortex (OFC). The OFC is a brain structure with an unusually high anatomical and functional connectivity. It receives input from all sensory modalities and maintains strong connections to cortical and subcortical regions, among others related to memory functions (e.g., the hippocampus and the entorhinal cortex; Price, 2006a,b). Being that interconnected makes it an ideal candidate for the proposed integration processes. Supporting a high-level integrative role of the OFC several studies have found its involvement in the perception of beauty, for example in vision (Kawabata & Zeki, 2004), music (Blood, Zatorre, Bermudey, & Evans, 1999; Ishizu & Zeki, 2011) and – specifically pointing at the connection between subjective beauty and understanding – mathematical formulas (Zeki, Romaya, Benincase, & Atiyah, 2014). Furthermore the OFC has repeatedly been reported to play a role in hypothesis testing (e.g., Damasio, 1996; Petrides, Alivisatos, & Frey, 2002) stressing its possible function in processing of stimulus information toward the detection of meaning. Regarding coherence judgments several studies have found the left orbitofrontal cortex (OFC) to be related to the intuitive perception of coherence in visual object recognition tasks (e.g., Bar et al., 2006; Horr, Braun, & Volz, 2014; Luu et al., 2010; Volz & Von Cramon, 2006). According to these studies, the OFC may serve as a global integrator that receives information from early visual areas and creates a coarse initial representation that forms the basis of an intuitive coherence judgment.

First results confirm that the OFC's specific involvement in the intuitive perception of coherence is not restricted to visual object recognition but can be found as well in auditory (Volz, Rübsamen, & von Cramon, 2008) and also semantic coherence judgments (Zander, Horr, Bolte, & Volz, in press). Based on these results and on the model put forward for the visual domain/object recognition, we propose that processing in the OFC serves to integrate remotely linked semantic concepts and thereby induces a feeling of coherence which in a subsequent step may lead to the common associate being explicitly nameable.

Conceiving of intuition by means of information integration, one can hypothesize that the format in which information is presented has a crucial influence on how it is processed, especially regarding temporal processing dynamics. According to the spreading activation theory, a successful integration depends on information arriving synchronously or in a certain time window of integration that allows the activation of related semantic concepts to overlap temporally. In this sense it can be hypothesized that participants perform worse and need more time to (intuitively) recognize coherence for a sequential as compared to a simultaneous presentation. As compared to spontaneous overlapping of activation in simultaneous presentation, where every word can be read directly after the previous one, this is because sequential presentation would require initial information to be actively maintained in memory until the next piece of information is revealed and can be connected to the others. On a neural level the gradual rather than immediate accumulation of information may require a different integration mechanism. That is, if information is not given all at once, but needs to be maintained in memory, another kind of integration process may be necessary. It is therefore questionable whether the proposed role of the OFC as integrator of information in intuitive coherence processing also holds for a sequential presentation.

Our experiments were designed with two purposes in mind: (1) We intended to investigate the involvement of the OFC in semantic coherence judgments and test to what extent the evidence for its role as a global integrator can be generalized over different domains. (2) We intended to test how intuitive coherence judgments are influenced by the temporal dynamics of stimulus presentation and therefore restriction to information accumulation, that is, when the words of a triad are presented all at once (simultaneously), as it has been done in previous experiments (e.g., Bolte et al., 2003; Bowers et al., 1990; Ilg et al., 2007), or one after the other (sequentially).

Due to its high temporal resolution we used magnetoencephalography (MEG) to disentangle the neural mechanisms involved in the intuitive perception of semantic coherence. Participants worked on a coherence judgment task, a modified version of Bowers et al.'s (1990) DTT. Specifically, our participants were presented with three frequently used words in their native language (German), which either did or did not have a common associate (in the following called associated and unassociated triads, respectively). They then had to say whether they thought the three words were related (coherent), and if so, whether they could identify the common associate. We hypothesized that in Experiment 1, with the triad words presented in the traditional simultaneous format (see Fig. 1B), we would replicate over-chance performance discriminating between associated and unassociated triads – as well when the common associate can as when it cannot be named – and find OFC activation that would be in accordance with its proposed role as a global integrator. For Experiment 2, with triad words being presented sequentially (see Fig. 1C), we assumed that an initial automatic spread of activation would be prevented by the sequential presentation format. If this would prevent an overlapping of activation, participants should therefore be unable to make coherence judgments, at least on the basis of a non-verbalizable feeling, with over-chance accuracy. Alternatively we may observe a different neural strategy that accounts for overlapping activation by enabling a later connection of activation maintained in working memory.

2. Experiment 1

In Experiment 1 we presented triads in the standard format, with the three constituent words appearing all at once, one underneath the other (simultaneous presentation). We hypothesized that on the behavioral level we would find the frequently observed over-chance discrimination between associated and unassociated triads on the basis of a non-verbalizable feeling of coherence.

In accordance with the proposed neural model of the OFC as a global integrator enabling coherence perception, we put forward the following neural hypotheses: (1) Activation in the OFC should be higher for triads judged to be coherent than for triads judged to be incoherent (subsequently referred to as coherent triads and incoherent triads). Note that coherent triads include both explicitly and implicitly coherent triads, in which the common associate is or is not named respectively. Based on Bower et al.'s (1990) notion of intuition as a gradual process the ability to explicitly name a common associate belongs to the second, that is, the "integrative" stage of intuitive processing. This "integrative" stage is always preceded by the first, the "guiding stage", from which the preliminary feeling of coherence emerges. In the present study we are interested in neural

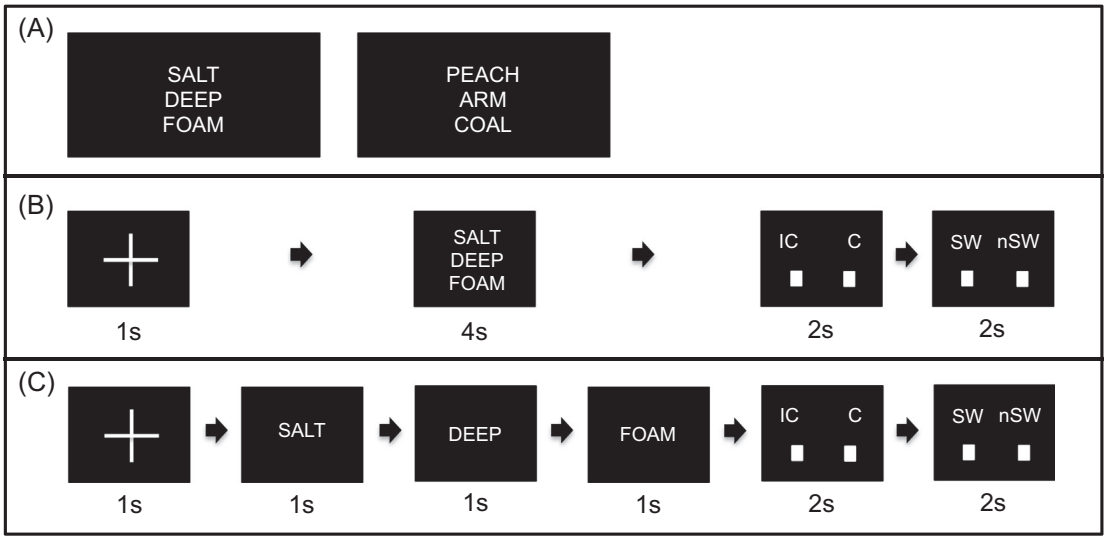

Fig. 1. Experimental paradigm stimuli, and procedure. (A) Example for an associated triad with the solution word sea and an unassociated triad. (B) Experimental trial in Experiment 1: After the fixation cross the triad appears on the screen for 4 s, subsequently appears the coherence judgment screen and participants have 2 s to answer via button pressing whether the triad was incoherent (IC) or coherent (C), if they answer with 'coherent' the solution judgment screen appears asking whether they can name a common associate (SW = solution word) or cannot name it (nSW = no solution word). They are aware that they will have to write down the common associate after the experiment, when they claim to know it. (C) Experimental trial in Experiment 2: Same as in Experiment 1 only that each word of a triad is presented on the screen individually for one second.

activation underlying exactly this preliminary feeling of coherence in the guiding stage, which should therefore be present in both explicitly and implicitly coherent triads. Increased activation in the OFC for coherent as compared to incoherent triads would demonstrate the specific role of the OFC in the subjective perception of semantic coherence. (2) Activation in other areas that are more active for coherence than for incoherence judgments and are thought to be related to memory processes and semantic retrieval should show a differentiation before the differentiation in the OFC is observed. This hypothesis is based on the assumption that upon the presentation of a triad, semantic concepts in memory are activated in parallel and subsequently sent onward to the OFC for integration. (3) In order to ensure that the activation difference between coherent and incoherent triads actually reflects the subjective perception of coherence, we have to make sure that this activation is not only due to differences in objective stimulus characteristics between associated and unassociated triads, with former being more often judged as coherent and latter more often as incoherent. We therefore test whether differential OFC activation between associated and unassociated triads, that is, a contrast solely based on objective stimulus characteristics rather than subjective judgments, can be observed. If this is not the case then OFC activation in a coherent versus incoherent contrast being due solely to stimulus characteristics can be ruled out. Though a differential activation in the OFC for objective stimulus types would obviously not exclude the OFC's substantial involvement in subjective perception, a lack of differences gives a strong hint that OFC activation in the comparison of response conditions actually represents a subjective feeling. (4) Similarly, there should be no differential activation between unassociated experimental and control trials in the OFC. In control trials participants were shown an unassociated triad knowing beforehand that it was unassociated and that they would not have to make a coherence judgment but simply press a button by the end of the presentation. The contrast between unassociated and control trials is crucial because it captures exactly the difference between making an attempt to make a coherence judgment and the lack of this attempt, while stimulus material is completely equal. A lack of OFC activation in the contrast between unassociated and control triads is therefore needed to demonstrate that the OFC does not solely reflect an attempt to find coherence.

2.1. Materials and methods

2.1.1. Participants

Twenty healthy students (13 female) from the University of Tübingen (age range, 20–31; mean age, 24.3 ± 3.2) completed the experiment for a payment of 12 Euros per hour. All participants had normal or corrected-to-normal vision, spoke German as their native language, and none had irremovable metal implants in their bodies. The experimental procedure and data collection followed the ethical guidelines of the "Declaration of Helsinki" (2012) and were approved by the local ethical committee of the University of Tübingen, Medical Department.

2.1.2. Stimuli and experimental paradigm

Stimuli used were triads each consisting of three German words. The triads could either be associated or unassociated. Associated triads were composed so that a common remote associate existed, that is, a fourth word linking the three constituent words. Unassociated triads simply consisted of three words randomly put together, and thus had no remote associate. Associated and unassociated triads differed only in the semantic relatedness of the three constituent words with the solution word but not in the pairwise semantic relatedness between one clue word to another. This lack of pairwise relatedness was ensured by prior pilot tests. Among the 200 triad stimuli used, 80 were taken from former German studies (Bolte et al., 2003; Ilg et al., 2007), 65 were translated from English into German (Bowden & Jung-Beeman, 2003a) and 55 were newly created for the current study. In a pilot study with 27 participants it was ensured that only triads that were rated coherent by more than 40 percent of participants were included as associated triads and only triads rated coherent by less than 30 percent of participants were included as unassociated triads. A relatively low cut-off percentage of 40%/30% for associated and unassociated triads respectively was chosen in order to have a sufficiently difficult task and make sure that a sufficient amount of participants' judgments are based purely on an undefined feeling of coherence rather than an immediate understanding of the common associate. There were no significant differences in word length ($t(198) = -0.132$, $p = 0.895$), number of syllables ($t(198) = 0.167$, $p = 0.867$), number of phonemes ($t(198) = 0.170$, $p = 0.865$), frequency (WebCelex, Max Planck Institute for Psycholinguistics, Nijmegen, 2001; $t(198) = 0.710$, $p = 0.479$), or concreteness (unpublished list by Christian Fiebach, used with permission; $t(198) = -0.896$, $p = 0.372$) between associated and unassociated triads. See Fig. 1A for an example of an associated and an unassociated triad and supplementary materials S1 for the complete list.

The paradigm was programmed with Presentation® 14.9 (Neurobehavioral Systems, Inc., San Francisco, California). In each trial the three constituent words of a triad were presented simultaneously, one below the other, and remained on the screen for 4 s. After the triad disappeared, participants had 2 s to decide (via button pressing) whether or not the presented triad had a common associate, that is, whether it was coherent (left index finger) or incoherent (right index finger). If they rated the triad as coherent, they had another 2 s to indicate (again via button pressing) whether they could actually name the common associate (index finger used for yes or no answers was counterbalanced across participants). Participants had been told prior to the MEG session that if they claimed to know a common associate for a triad, they would be shown that triad again outside the scanner and would then have to write down the common associate.

The paradigm results in a fully factorial 2×3 design. Factor 1 is objective triad type: (1) associated and (2) unassociated. Factor 2 is response conditions: (1) the triad was classified as coherent and participants claimed to know the common associate (subsequently called explicitly coherent triads), (2) the triad was classified as coherent and participants said they do *not*

know the common associate (subsequently called implicitly coherent triads), and (3) the triad was classified as incoherent (subsequently called incoherent triads).

A timeline for an experimental trial in Experiment 1 is given in Fig. 1B. Each participant had to make a coherence judgment for 100 associated and 50 unassociated triads. In addition to these 150 experimental trials, 50 control trials were used. With the appearance of a red fixation cross indicating a control trial, participants were always aware that they were being presented with an unassociated triad. They received the instruction to read the three words but to refrain from attempting to make a judgment. After the triad disappeared, they simply had to press one of the two response buttons.

2.1.3. Experimental procedure and recording

The study was conducted at the MEG Center of the University of Tübingen. Participants were seated on a height-adjustable chair inside a magnetically shielded room (Vakuumschmelze, Hanau, Germany). Before the recording participants were asked to change into hospital clothing and remove all jewellery in order to ensure no metallic objects were carried into the scanner. Neuromagnetic recordings were obtained via a 275-sensor, whole-head MEG system (VSM Medtech, Port Coquitlam, BC, Canada). The visually presented word stimuli were projected via a standard video projector onto a screen in the recording room that was placed about 60 cm away from the participants.

The experimental session took about half an hour. After thoroughly going through the instructions, the task began with a training sequence of 12 trials, for which behavioral data and brain activation was not analyzed. When participants stated that they had understood the task and had no further questions, the experimental blocks started. The 200 triads were presented in four blocks and fully randomized in sequence for each individual participant. In order to avoid the implicit assumptions of a 1:1 ratio between associated and unassociated triads and a therefore too conservative response strategy participants had been told in advance that the ratio between associated and unassociated triads was 2:1 and were asked to try adjusting their answers according to this ratio.

The MEG-signal was recorded continuously, with a sampling rate of 585.938 hertz (Hz). A participants' head position with respect to sensor positions was measured for every block, participants' head were kept in place using appropriate pads and so it was ensured that head movement remained lower than 5 mm. To ensure that the timing of the measurement was not influenced by the delay introduced by the video projector, each event (i.e., fixation cross, word triad, coherence judgment screen, common associate judgment screen) was encoded via white rectangles in the right corner of the screen. The rectangles were not visible to the participant but were recorded via photo-diodes. Those recordings were later used to determine the exact onset of events. In addition, stimulus type (associated, unassociated, or control) and response in experimental trials (explicitly coherent, implicitly coherent, or incoherent) were recorded by the MEG system via digital triggers.

2.1.4. MEG analysis

MEG data were analyzed with Matlab 8.1 (the MathWorks, Natick, Massachusetts) and the Matlab-based software packages Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011) and Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011). The Fieldtrip software was used for preprocessing and timelocked averaging over epochs on the sensor level. For preprocessing, the continuous recordings of each block were filtered with a 0.1 Hz high-pass and 100 Hz low-pass filter and were segmented into epochs of 5 s, spanning 1000 ms before stimulus onset, that is, the onset of the triad on the screen, to 4000 ms after stimulus onset, with 200 ms before onset being used for baseline correction.

Treatment of artifacts was handled so that the least possible amount of data was lost. For each block, bad channels, showing ongoing magnetic artifacts (activities stronger than ±1 pT) were removed and interpolated, that is, replaced by the average of their neighboring sensors. No more than 10 sensors had to be interpolated in any block. Channels with few occasional artifacts were kept, and the corresponding epochs were rejected. No more than 20% of epochs in any of the conditions (responses and stimulus types) had to be rejected for any participant (mean per participant 3.4% ± 2.0). Each participant's epochs were averaged time-locked to stimulus onset. This was done separately for the conditions. The same number of epochs was used for the average of the conditions that were planned to be tested against each other, that is, (1) stimulus types and (2) participants' responses, in order to make sure that those conditions did not systematically differ in noise level.

On the basis of the time-locked averages, source activations were estimated using the depth-weighted minimum L2 norm estimator of cortical current density on a mesh representing the cortical surface (for a detailed description, see Hämäläinen and Ilmoniemi, 1994) as implemented in the Brainstorm software. The source estimation was normalized using the noise covariance matrix (as described by Dale et al., 2000), calculated separately for each participant over all conditions, from the 1-s pre-stimulus time span. The underlying forward model was computed using the method of overlapping spheres as described by Huang, Mosher, and Leahy (1999). Given that no individual anatomies from magnetic resonance imaging (MRI) data were available, the forward model was based on the MNI/Colin27 template that is implemented in the Brainstorm software. The template was warped to fit participant's individual digitized head points. For technical details, see Leahy, Mosher, Spencer, Huang, & Lewine, 1998.

One performance-dependent (coherent versus incoherent triads) and two stimulus-dependent contrasts (associated versus unassociated and unassociated versus control triads) were calculated. Clusters are reported as activated for a specific contrast, where more than 20 adjacent vertices of the triangulated cortical surface differ significantly ($p < 0.01$) between the compared conditions for the mean over either (1) 0–2000 ms or (2) for 2000–4000 ms after stimulus onset, that is, the onset of the presentation of the triad (all three triad words together) on the screen. The activation within a cluster was quantified as the root mean squares of the source activation at all vertices within the cluster. The analyzed time span

of 0–4000 ms entails the exact amount of time in which the three triad words were presented and exclude any possible confounding of the neuromagnetic response with the subsequent motor response. For defining activated clusters the time of triad presentation was cut into two segments in order to disentangle earlier and later stimulus processing. Exact time courses of activated clusters were evaluated over the entire time span. Repeated measurement *t*-tests between conditions at every sampling point of an activated cluster were conducted, with time spans showing a significant difference ($p < 0.01$) at every sampling point for more than 400 ms being reported as significant. Cluster size (number of adjacent significant vertices) and length of time spans (number of adjacent significant sampling points) therefore served to correct for multiple comparisons.

2.2. Results

2.2.1. Behavioral results

Across all experimental trials, participants rated a mean of 40.4 (±12.3) percent as coherent. For the triads rated as coherent, they claimed to be able to name a common associate for 68.8 (±17.68) percent. An overview of the mean frequency of participants' responses for the different stimulus types is given in Fig. 2A. When responses were analyzed in the framework of signal detection theory (see Abdi, 2007), the mean hit rate among associated triads was 55.5 (±14.2) percent and the mean false alarm rate among unassociated triads was 10.4 (±9.3) percent. The parameters d' and C were estimated from hits and false alarms. D' serves as a measure of task difficulty defined as the difference between the standardized hit and standardized false alarm rate. It ranges from zero, reflecting chance performance to infinity, with values over four accounting for nearly perfect performance. The mean d' in Experiment 1 was 1.65 (±0.37), test against zero: $t(19) = 20.00$, $p < 0.001$, $dz = 4.2$ demonstrating participants' over-chance performance in discriminating between associated and unassociated triads.. The criterion C is a measure of bias and defined as the mean of the standardized hit and false alarm rate. It ranges from −1 to 1, with negative values reflecting a liberal, positive values a conservative, and zero an unbiased response strategy. The given

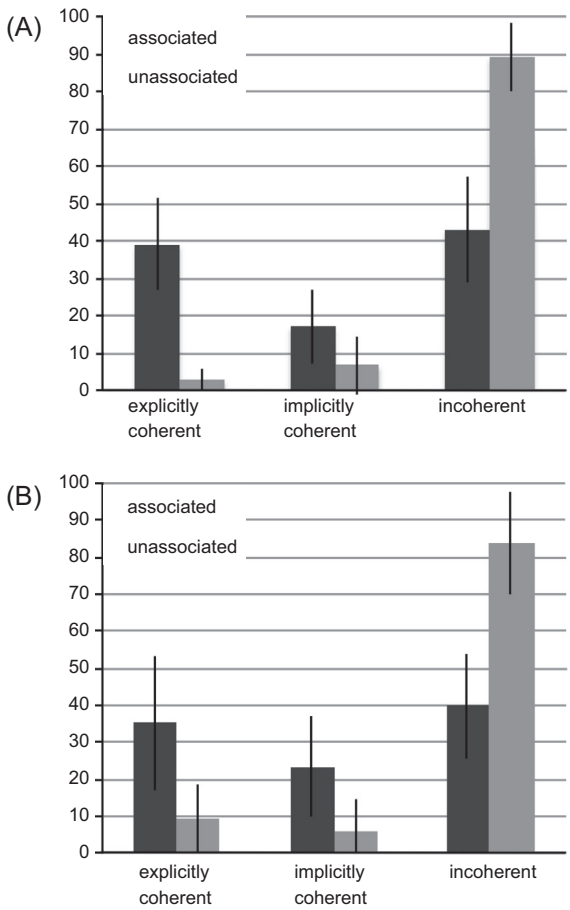

Fig. 2. Frequencies (percentage ± std) of the three responses (explicitly coherent, implicitly coherent and incoherent) for both stimulus types (associated and unassociated) in (A) Experiment 1 and (B) Experiment 2.

mean value of C was 0.60 (±0.4), test against zero: $t(19) = 6.23$, $p < 0.001$, $dz = 1.3$ demonstrating participants' tendency to judge triads as incoherent.

To test whether participants were able to discriminate between associated and unassociated triads over chance, even without being able to identify the common associate, the intuition index as defined by Bolte et al. (2003) was used. The intuition index is determined by excluding all triads in which the common associate is given (i.e., all explicitly coherent triads) and then calculating the difference between hits (i.e., proportion of implicitly coherent associated triads) and false alarms (i.e., proportion of implicitly coherent unassociated triads). In Experiment 1 the intuition index was 25.77% (±8.9). This significantly exceeds chance level zero, $t(19) = 8.08$, $p < 0.001$, $dz = 1.7$, and is in the same order of magnitude as results from former studies applying DTT-like paradigms (e.g., Bolte et al., 2003: 13%; Ilg et al., 2007: 28.6%).

Mean reaction times are given in Table 1. A two (stimulus type) by three (response) repeated measure ANOVA revealed no main effects of stimulus type, associated vs. unassociated, $F(1,8) = 1.062$, $p = 0.333$, or judgment, explicitly coherent vs. implicitly coherent vs. incoherent, $F(2,16) = 3.53$, $p = 0.540$. The interaction, $F(2,16) = 3.118$, $p = 0.072$, was close to significant with correct answers (hits and correct rejections) tending to be given more quickly than incorrect ones (misses and false alarms).

2.2.2. MEG results

The MNI coordinates, size, and significant time spans of activated clusters (in all three contrasts) can be seen in Table 2. The mean over the early presentation time span (0–2000 ms) in the crucial performance-dependent contrast (coherent versus incoherent triads) revealed no activated cluster. The main differentiation in activation between triads judged as coherent and those judged as incoherent occurred more than two seconds after stimulus presentation. As proposed in hypothesis (1), OFC activation in the left hemisphere was higher for coherent than for incoherent triads, from 2331 ms after stimulus onset until the end of stimulus presentation. In accordance with hypothesis (2), this differential activation started latest in the OFC as compared to other regions with significantly stronger activation for coherent as compared to incoherent triads. The first region that was more strongly activated for coherent than for incoherent triads was the left middle frontal gyrus, at around 1800 ms. Significant activation was further found in the left insular cortex, the left parahippocampal gyrus, the left amygdala, and the left cingulate gyrus. Those reached significance slightly later, between 2100 and 2300 ms. All activated clusters are displayed in Fig. 3. Fig. 4 shows the time courses of activation for the OFC and the middle frontal gyrus.

To test our hypotheses (3) and (4), we calculated the stimulus-dependent contrasts between associated and unassociated triads and between unassociated and control triads. Different to the performance-dependent contrast, no stimulus-dependent contrast activation was found in any left orbitofrontal cluster. To verify the lack of left OFC activation in our two control contrasts we analyzed the OFC cluster that was significant in the performance-dependent contrast at every sampling point. Neither of the two stimulus-dependent comparisons showed a significant difference in this cluster at any multiple-comparison corrected time span.

2.3. Discussion

Results from Experiment 1 fit our proposed neuro-cognitive model of intuitive coherence judgments that we based on findings from previous studies in visual object recognition (Bar et al., 2006; Horr et al., 2014; Volz & Von Cramon, 2006). The lack of an activated cluster in the mean over the early presentation time span (0–2000 ms) makes sense assuming that individual semantic concepts have to be processed before a network of activation regarding related concepts can spread out. For the mean over the late presentation time span (2000–4000 ms), differential activation between coherent and incoherent triads was in accordance with hypotheses (1) and (2). OFC activation in the left hemisphere was found to increase for triads judged as coherent as compared to those judged as incoherent (hypothesis 1). The other activated areas are assumed to be related to memory and emotional processes crucial for the retrieval of semantic concepts and the hypothesized spread of activation. The middle frontal gyrus has been suggested to be related to the storage as well as retrieval of information in working memory (e.g., Leung, Gore, & Goldman-Rakic, 2002). Thompson-Schill, D'Esposito, Aguirre, and Farah (1997) furthermore pointed out this region's specific involvement in comparison of competing alternatives from semantic memory and Eldridge, Knowlton, Furmanski, Bookheimer, and Engel (2000) showed that it is activated specifically for recognition (rather than recall) of semantic information. The amygdala, parahippocampal gyrus, cingulate gyrus and insula gyrus are regions that belong to the limbic system, closely related to memory and emotional functions (e.g., Bermudez-Rattoni, Okuda, Roozendaal, & McGaugh, 2005; Markowitsch, 1995; Morgane, Galler, & Mokler, 2005; Squire & Zola-Morgan, 1991). The cingulate gyrus has further been specifically associated with semantic retrieval and tip-of-the-tongue phenomena (e.g., Heun et al., 2006; Maril, Wagner, & Schacter, 2001). All these regions displayed activation earlier than the OFC (hypothesis 2). Differential activation in the stimulus-dependent contrasts, that is, between associated and unassociated and between unassociated and control trials did not involve the left OFC (hypotheses 3 and 4). Left OFC activation increase being solely found in the performance-dependent contrast, that is, between triads that induced a subjective feeling of coherence versus those that did not and a lack of this activation in the stimulus-dependent contrasts demonstrates that the OFC does not simply represent different processing due to the objective-stimulus categories (associated versus unassociated) or task demands (unassociated versus controlled). Therefore left OFC activation can be interpreted as reflecting the actual subjective perception of coherence. OFC activation following activation in areas related to semantic retrieval as well as general memory- and emotion-related areas is in accordance with the notion of the OFC serving as a global integrator that merges

Table 1
Mean reaction times (ms after response-time onset) for the different stimulus types and responses.

Stimulus type	Response		
	Explicitly coherent	Implicitly coherent	Incoherent
Simultaneous presentation (Experiment 1)			
Associated triad	651.15(±136.37)	786.78(±136.366)	750.72(166.73)
Unassociated triad	783.05(±291.24)	888.74(±356.21)	635.88(165.35)
Sequential presentation (Experiment 2)			
Associated triad	672.91(±186.91)	699.37(±203.87)	790.92(±189.16)
Unassociated triad	703.88(±299.42)	845.65(±211.10)	734.88(±234.29)

Table 2
Anatomical specifications, MNI coordinates, vertices and significant time spans for clusters activated in the performance and the stimulus depend contrasts in Experiment 1.

Region	MNI coordinates			Vertices (number)	Time spans (ms)
	x	*y*	*z*		
(1) Performance dependent contrast: Coherent > incoherent					
Left orbitofrontal cortex[b]	−24	48	−9	129	2331–2811 2861–3391 3396–4000
Left postcentral gyrus[b]	−57	−16	51	80	2659–2993 3325–3777
Left cingulate gyrus[b]	−2	26	15	56	2115–4000
Left insular cortex[b]	−32	−14	12	137	2195–4002
Left amygdala[b]	−16	−6	−12	65	2248–4000
Left parahippocampal gyrus[b]	−17	−15	−23	53	2255–3391 3395–4000
Left middle frontal gyrus[b]	−32	14	12	64	1790–4000
(2a) Stimulus dependent contrast: Associated > unassociated					
Right orbitofrontal cortex[a]	17	8	−17	121	809–1232
Right fusiform gyrus[a]	26	−43	−11	194	794–1203
Left subcallosal cortex[a]	−2	22	−24	58	809–1173
Right frontal pole[a]	34	48	−13	54	786–1213
(2b) Stimulus dependent contrast: Unassociated > control					
Left occipital gyrus[a]	−22	−86	−11	266	783–1386
Right cingulate gyrus[a]	7	−31	50	385	812–2418
Left lateral occipital gyrus[a]	−11	−64	−61	209	236–614
Right superior frontal gyrus[b]	19	20	41	88	1452–4000
Right lateral occipital gyrys[b]	33	−84	148	535	234–944 951–1478
Left supramarginal gyrus[c]	−59	−46	40	463	872–3944

All time spans significant with $p < 0.01$ for each sampling point in more than 400 ms as well as the mean of the given time span are listed for each cluster. MNI coordinates are from the maximally activated vertex.
[a] All clusters significant over the mean of 0–2000 ms.
[b] All clusters significant over the mean of 2000–4000 ms.
[c] All clusters significant over the mean of both with time spans.
Clusters with $p < 0.01$ for more than 20 adjacent vertices are listed for each contrast.

incomplete stimulus input and memory content into a coarse representation on the basis of which the feeling of coherence is created.

Recent studies, in agreement with the current experiments, suggest that this hypothesized role is generalizable over information from different modalities (Volz et al., 2008; Zander et al., in press). Specifically, for the semantic domain, the activation of memory-related areas fits well with the idea of a partial activation of close and remote associates of semantic concepts. It may reflect the (partial) activation of semantic concepts associated with the triad words that are then signaled onward and integrated in the OFC. The integration in the OFC toward a coarse representation of the gist of information is at a subjective level considered to represent the implicit feeling of coherence and may further be associated with a perceived ease of processing and positive affect which has been reported to accompany and facilitate intuitive judgments (e.g., Topolinski & Strack, 2009).

The most striking difference between results from object recognition tasks and our study on semantic judgments is the temporal dynamics. In the domain of visual object recognition, the OFC was found to be one of the earliest regions to show a differential activation (Bar et al., 2006; Horr et al., 2014; Luu et al., 2010). On this basis, the OFC was proposed on as an early

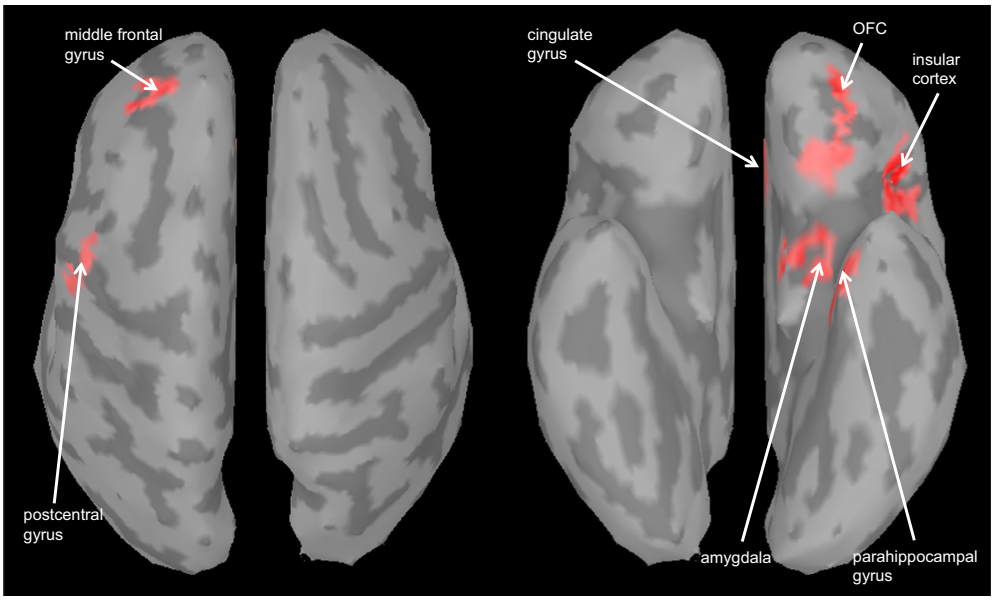

Fig. 3. Activated clusters in the performance-dependent contrast in Experiment 1. All clusters larger than 20 vertices with significantly ($p < 0.01$) higher activation for coherent as opposed to incoherent triads are shown in red.

integrator, receiving direct input from early sensory regions, processing it toward a coarse percept that biases the coherence judgment, and only then signaling it onward to further object-processing areas. However the late activation of the OFC in semantic coherence makes sense, when one takes into account conceptual differences between basic visual processing and semantic processing. Coherence judgments in a visual object-recognition task would be based on line drawings with missing pixel information. If the pixels are in their original order, the underlying object is still somewhat recognizable (the equivalent of an associated triad). But if the pixels are randomly mixed up, no coherent object can be recognized anymore (the equivalent of an unassociated triad). Such object recognition judgments are much more specific to one sensory (the visual) domain. Furthermore, they are based on low-level stimulus information (the fragments of the line drawing). The processing of these fragments can therefore be assumed to be completed in early visual areas. However, those early visual areas may not make a difference in the processing of fragments that are later integrated as coherent and the processing of those that are not. The OFC would then be responsible for an early integration and a coarse holistic representation of these fragments, which may or may not lead to an initial perception of coherence. For the subject to finally retrieve the full semantic concept (name of the object) underlying the feeling of coherence, this coarse representation needs to be sent onward to higher-level object-recognition areas. However, for an assessment of coherence in the semantic task, the fragments to be put together are by themselves meaningful semantic concepts. Therefore, higher-level semantic processing activating a semantic network as proposed in the spreading activation theory needs to take place in advance of or at least overlapping with the evaluation of any kind of semantic connection between the words. The semantic associations related to triad words would then be the equivalent of the fragments in the visual task that are signaled onward to the orbitofrontal cortex for initial integration. Given that the individual semantic concepts underlying the triad words are already retrieved, it is questionable which further processing steps would be necessary after their integration. And given that we did not find any regions being active for the coherent versus the incoherent contrast at a later point in time, it may simply be the accumulation of semantic associations in the OFC that finally leads from an initial implicit to an explicit understanding of the common associate between the triad words. This fits with Bower et al.' (1990) idea of a continuous passage between two stages of intuition—from the "guiding stage," in which cues of coherence are being accumulated, to the "integrative stage," where a threshold of accumulation is crossed leading to an explicit representation.

Regarding the idea of spreading activation and accumulation, it seems crucial that different semantic concepts are being activated and reach the OFC at the same time, that is, in a certain window of integration. Experiment 2 was therefore designed to address the question of how processing mechanisms are different when semantic concepts are not automatically activated at the same time, that is, are not presented simultaneously, all at once, but sequentially, one after the other.

3. Experiment 2

To investigate the influence of the temporal dynamics in which information is presented in Experiment 2 we applied the triad task, but with the words of a triad presented sequentially, that is, one after the other. In this way, we set out to

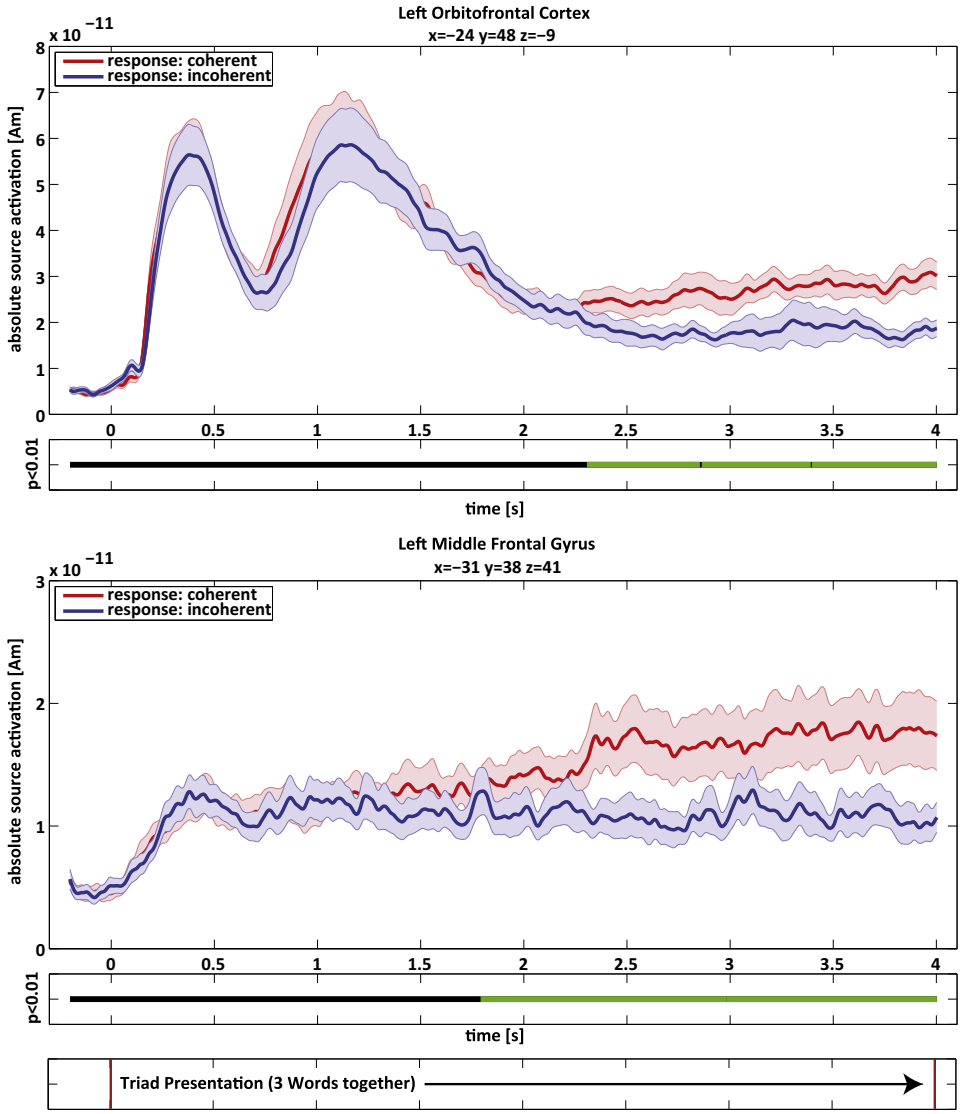

Fig. 4. Time courses of activation in the left orbitofrontal cortex (top) and the left middle frontal gyrus (bottom) in Experiment 1, surrounded by their standard error. Time in seconds is plotted on the *x*-axis with zero being the onset of the triad presentation. Red curves show activation in triads that were rated coherent, blue curves activation in triads that were rated incoherent. Below each graph are the time spans (in green) with a significant ($p < 0.01$) difference in the performance-dependent contrast at each sampling point for more than 400 ms.

differentiate among three possibilities regarding the influence of a sequential presentation: A sequential presentation might prevent an overlapping of activated concepts and therewith the Gestalt-like intuitive perception of coherence. Thus, due to this presentation format, an initial feeling of coherence might not be generated at all, which could be reflected via a chance performance in the behavioral results (possibility 1). On the other hand, an overlapping of activation might be maintained actively by a different integration mechanisms that leads to similar behavioral results but differences in neural findings compared to those in Experiment 1 (possibility 2). What exactly those differences would be and to what extent the integration could still be accounted for by the OFC could not be predicted. Lastly, it is as well conceivable that automatic activation overlap is still given if each word is presented with one second delay to the next one and the neural integration mechanisms proposed for simultaneous presentation also apply to the sequential format. In this case results from Experiment 1 and Experiment 2 would be expected to be very similar, behaviorally as well as neurally (possibility 3). In order to be able to distinguish between the three possibilities in a direct comparison of Experiments 1 and 2, we calculated the same analyses and contrasts in Experiment 2 as we did in Experiment 1.

3.1. Materials and methods

3.1.1. Participants

Twenty-four healthy students (10 female) from the University of Tübingen (age range, 18–29; age mean, 23.6, ±3.0) completed the experiment for a payment of 12 Euros per hour. Inclusion criteria and ethical regulations were the same as those in Experiment 1. None of the participants of Experiment 2 participated as well in Experiment 1.

3.1.2. Experimental procedure and MEG analysis

Stimuli were identical to those in Experiment 1. The experimental paradigm was also identical, except for the presentation of the word triads. In Experiment 2 the constituent words of a triad were presented sequentially, with each word remaining on the center of the screen for 1 s. Participants therefore had to keep each word in mind in order to determine the common associate after the presentation of the third word. The timeline of an experimental trial in Experiment 2 can be seen in Fig. 1C.

For the MEG analysis, the continuous recordings of each block were cut into epochs ranging from 1000 ms before stimulus onset to 5000 ms after stimulus onset, with stimulus onset being the onset of the first word of the triad. Again 200 ms before stimulus onset was used for baseline correction. Apart from the length of the epochs, preprocessing and source reconstruction were handled in the same manner as described for Experiment 1. During artifact correction a mean of 3.2% (±2.1) of epochs were rejected for each participant. Activated clusters were defined according to the mean activation over all points in time (1) for 2000–3000 ms after stimulus onset, that is, the presentation of the third triad word and (2) for 3000–5000 ms after stimulus onset, that is, the response time frame. Time span (1) encompassed the presentation of the last triad word as this is the time span during which participants received the last piece of information needed to judge whether or not there was a common associate linking all three triad words. Since time span (1) does not overlap with the time span of button pressing, possible confounding of neuromagnetic responses with the subsequent motor responses was excluded. Similar to the 0–2000 ms timespan in Experiment 1, there seemed to be little processing differences in this time span (1), indicating that it is too early to track the evolving feeling of subjective coherence. We therefore decided to include time span (2), the two second response time frame. Note that this time span does of course encompass the motor responses. Exact time courses were evaluated over the entire duration of a trial including presentation of all three words as well as the 2 s response time frame. In order to enable comparison to Experiment 1, in which all triad words were presented simultaneously and track the accumulation of information leading to participants' subjective feeling of coherence (or incoherence) the three words and the response time frame were not analyzed separately, but as one continuous epoch.

3.2. Results

3.2.1. Behavioral results

Among all experimental trials, participants rated a mean of 44.1 (±13.8) percent as coherent, and they claimed to be able to name the common associate for 56.5 (±20.72) percent of those trials. An overview of the mean frequency of participants' responses for the different stimulus types is given in Fig. 2B. The mean hit rate was 58.7 (±14.5) percent and the mean false alarm rate 10.4 (±9.3) percent. This led to a mean d' of 1.4 (±0.50), test against zero: $t(23) = 24.02$, p against zero < 0.001, $dz = 5.0$. Like in Experiment 1 the criterion C of 0.412 (±0.455), test against zero: $t(23) = 4.25$, $p < 0.001$, $dz = 0.9$, reflects an overall conservative response strategy. The mean intuition index was 20.69 (±11.5), test against chance performance zero: $t(23) = 7.72$, $p < 0.001$, $dz = 1.6$.

Mean reaction times of coherence judgments for the different stimulus types and responses are given in Table 1. A two (stimulus type) by three (response) repeated measure ANOVA revealed no main effects of stimulus type, associated vs. unassociated, $F(1,11) = 3.124$, $p = 0.105$, or judgment, explicitly coherent vs. implicitly coherent vs. incoherent, $F(2,22) = 1.144$, $p = 0.337$. However, the interaction between the two factors was significant, $F(2,22) = 4.641$, $p = 0.021$, $\eta_p^2 = 0.30$, with correct answers (hits and correct rejections) given more quickly than incorrect ones (misses and false alarms).

Cross study comparisons indicated that participant performance (d') was not significantly different in the simultaneous and the sequential task, $t(42) = 1.09$, $p = 0.28$, and there was no significant difference in bias as measured by C, $t(42) = 1.50$, $p = 0.14$. Most interestingly, the intuition index did not significantly differ between Experiments 1 and 2, $t(42) = 0.99$, $p = 0.33$. That is, participants seemed to be equally able to intuitively discriminate between associated and unassociated triads, whether the triads were presented simultaneously or sequentially. Also, reaction times did not significantly differ between the simultaneous and sequential presentation (p for each condition > 0.3).

3.2.2. MEG results

The MNI coordinates, size, and significant time spans of activated clusters in all contrasts can be seen in Table 3. The mean over the entire time span of the last word presentation (2000–3000 ms) in the performance-dependent contrast (coherence vs. incoherence judgments) revealed an increase of activation in the left lateral occipital cortex for coherence judgments. For the mean over the response time frame (3000–5000 ms), significant clusters were found in the right orbitofrontal cortex, the left middle temporal gyrus, the right occipital pole, and—given that the answer "coherent" required a button press using the right hand—the left precentral gyrus. Strikingly, the absolute activation in all regions—except for the left lateral occipital cortex and, of course, the left precentral gyrus—was higher for incoherent than for coherent stimuli. Only in the left lateral

Table 3
Anatomical specifications, MNI coordinates, vertices and significant time spans for clusters activated in the performance and the stimulus depend contrasts in Experiment 2.

Region	MNI coordinates			Vertices (number)	Time spans (ms)
	x	*y*	*z*		
(1) Performance dependent contrast: Coherent > incoherent					
Left precentral gyrus[b]	−30	−20	74	109	3514–5000
Left lateral occipital cortex[c]	−27	−88	38	67	2255–2698 3226–3753 4059–5000
Incoherent > coherent					
Left middle temporal gyrus[b]	−56	−1	−35	86	3264–5000
Right orbitofrontal cortex[b]	34	48	−13	76	3297–5000
Right occipital pole[b]	23	−96	−20	178	3299–5000
(2a) Stimulus dependent contrast: Unassociated > associated					
Right intracalcarine cortex[b]	24	−66	7	130	3704–4436
Right lingual gyrus[b]	17	−67	−13	109	3722–4862
Right middle temporal gyrus[b]	64	−55	11	63	3284–4661
(2b) Stimulus dependent contrast: Unassociated > control					
Left central opercular cortex[a]	−52	7	2	193	1818–3340
Left precentral gyrus[a]	−1	−19	61	142	2197–3116
Left lateral occipital cortex[a]	−44	−80	−17	507	1121–1592 1601–2133 2159–3616
Right supramarginal gyrus[a]	39	−37	40	67	2225–2782
Right cingulate gyrus[b]	12	−49	5	387	3857–5000
Right lingual gyrus[b]	25	−47	−6	219	3898–4840
Right lateral occipital gyrus[b]	46	−74	27	72	3125–4134 4137–5000

All time spans significant with $p < 0.01$ for each sampling point in more than 400 ms as well as the mean of the given time span are listed for each cluster. MNI coordinates are from the maximally activated vertex.
[a] All clusters significant over the mean of 2000–3000 ms.
[b] All clusters significant over the mean of 3000–5000 ms.
[c] All clusters significant over the mean of both with time spans.
Clusters with $p < 0.01$ for more than 20 adjacent vertices are listed for each contrast.

occipital cortex did the first differentiation time span start during presentation of the third word, at 2255 ms. But activation also remained higher in this occipital cluster for coherent stimuli than it did for incoherent stimuli for significant time spans in the response frame (3226–3753 and 4059–5000 ms). The right OFC showed a higher activation for incoherent triads, from 3297 ms until the end of the response time frame. Its activation began to differ at around the same time as did activation in the left middle temporal gyrus (3264 ms) and the right occipital pole (3299 ms). All activated clusters in the performance-dependent contrast can be seen in Fig. 5. The time courses for the right OFC and the left lateral occipital cortex, are shown in Fig. 6.

The stimulus-dependent contrast between associated and unassociated as well as between unassociated and control triads revealed no significant clusters in the orbitofrontal cortex (hypothesis 3 and 4). The right OFC cluster that was significant in the performance-dependent contrast showed no significant difference at any time-span in the stimulus-dependent contrasts.

4. Discussion

Like in the simultaneous presentation differential OFC activation between coherent and incoherent triads was found in the sequential presentation format and may be attributed to subjective coherence processing supposedly taking place in the "guiding stage" (Bowers et al., 1990) of intuition (hypothesis 1). However, in this case the activation cannot reflect an initial feeling of coherence, given that it increased for incoherence rather than for coherence judgments. Furthermore, the other regions that were activated are basic visual (left lateral occipital cortex, right occipital pole) and semantic (left middle temporal gyrus) areas. That is, they are not regions associated with memory processing and the retrieval of information from semantic networks but rather seem to be involved in general stimulus processing. Activation in most regions occured at about the same time as it did in the OFC (in accordance with hypothesis 2). An exception from this was the lateral occipital cortex, which was the only one that had stronger activation for coherent instead of incoherent triads and the only one that

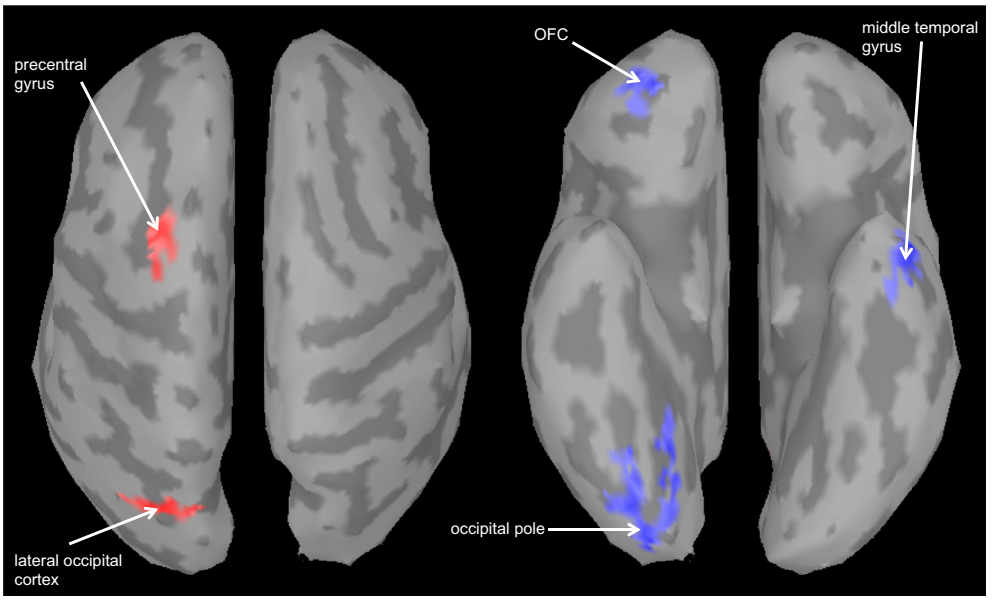

Fig. 5. Activated clusters in the performance-dependent contrast in Experiment 2. All clusters larger than 20 vertices with significantly ($p < 0.01$) higher activation for coherent as opposed to incoherent triads are shown in red. Those with higher activation for incoherent as opposed to coherent triads are shown in blue.

seemed to trace a sensory accumulation process from triad word to triad word rather than only starting to differentiate after presentation of all triads. The stimulus-dependent contrast between associated and unassociated as well as between unassociated and control triads revealed no significant clusters in the orbitofrontal cortex (hypothesis 3 and 4). The right OFC cluster that was significant in the performance-dependent contrast showed no significant difference at any time-span in the stimulus-dependent contrasts. OFC activation observed during sequential presentation in the performance-dependent contrast could therefore not be representing objective stimulus characteristics.

In sum, the neural results with sequential presentation showed three striking differences from the results of the traditional simultaneous-presentation format. (1) OFC activation was found in the right and not in the left hemisphere. (2) This OFC activation pointed in the opposite direction from that of the simultaneous presentation: It was stronger for triads in which no coherence could be detected. And (3) in contrast to Experiment 1, basic visual and semantic processing areas (as opposed to regions related to semantic working memory and emotional associations) were activated in the performance-dependent contrast. What might underlie such a drastic switch of the neural strategy in solving intuitive coherence judgments due solely to the manner of stimulus presentation? The model proposed to explain activation of the left orbitofrontal cortex assumes that this region is an integrator of partially activated concepts, and that the partial activation leads to an initial feeling of coherence in the "guiding stage" (Bowers et al., 1990) of intuitive judgment that serves as the basis for a later explicit recognition of the common associate. This quick and automatic integration of concepts not yet fully processed may be prevented by the sequential presentation of the word triad. Perhaps by the time the second word is presented, activation regarding the first word, including its associates, is already diminished. For that reason, integration in the left OFC enabled via automatic simultaneous activation of overlapping concepts may not be possible. However, participants are clearly able to make over-chance judgments even without naming the common associate. This demonstrates that the overlapping of activation and thereby over-chance intuitive coherence judgments must be enabled via another mechanism.

Generally, the right hemisphere has been related to a widespread activation of semantic fields as compared to relatively small semantic fields within the left hemisphere (e.g., Kounios & Beeman, 2014). This would fit to our finding of an early right OFC activation in the stimulus-dependent contrast between associated and unassociated triads. Though associated triads may fail to lead to sufficient overlapping activation in the integration phase and therefore not trigger the judgment "coherent", their overall stronger remote connections may still cause an increased right hemispheric activation spread as compared to unassociated triads right after all words have been read. Why however would we find an increase of right OFC activation for the subjective feeling of incoherence at a much later point in time, when stimuli are presented sequentially?

A possible explanation for the right OFC activation in sequential triad presentation may be found in the literature on the role of the right hemisphere in solution-related processing. Bowden and Jung-Beeman (1998, 2003b) have conducted a line of experiments relating the solution of insight problems specifically to the right hemisphere. Insight is a concept that is often associated with intuition, but which also has some fundamentally different aspects. As investigated in classical insight problem-solving tasks, insight has been defined as a sudden and surprising solution that comes to the problem solver's mind after an impasse and without his or her being able to report any strategy of problem solving (e.g., Cranford & Moss, 2012;

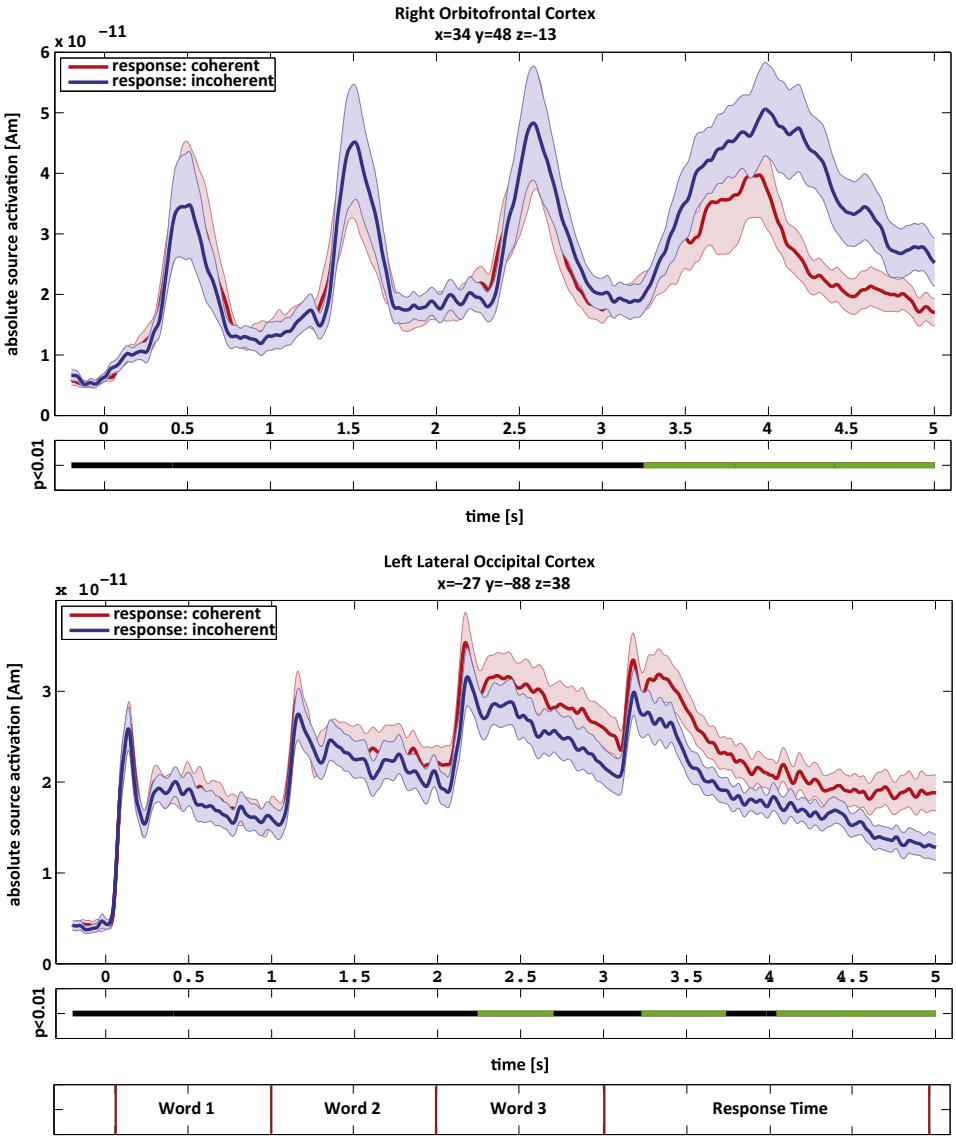

Fig. 6. Time courses of activation in the right orbitofrontal cortex (top) and the left lateral occipital cortex (bottom) in Experiment 2, surrounded by their standard error. Time in seconds is plotted on the *x*-axis with zero being the onset of the first word of the triad, 1 being the onset of the second word, 2 of the third word and 3 of the response screen. Red curves show activation in triads that were rated coherent, blue curves activation in triads that were rated incoherent. Below each graph are the time spans (in green) with a significant ($p < 0.01$) difference in the performance-dependent contrast at each sampling point for more than 400 ms.

Bowden & Jung-Beeman, 1998). In contrast to intuition's continuous processing from an initial feeling of coherence to an explicit recognition of the underlying association, insight mechanisms may indicate a representational change (e.g. Knoblich, Ohlsson, Haider, & Rhenius, 1999; Knoblich, Ohlsson, & Raney, 2001). That is, in insight problem-solving tasks, participants may, instead of gradually building up to the answer, have to reassess the problem to finally arrive at the solution. Bowden and Jung-Beeman (1998, 2003b) found that participants showed a greater priming effect toward words in a semantic insight solution task when the words were presented to participants' left visual field (i.e., the right hemisphere) rather than to their right one (i.e., the left hemisphere). Finding that this right hemisphere advantage was only present for problems that were presented for a long enough period of time (in their experiment, 7 s), Jung-Beeman and Bowden (2000) propose that right hemispheric activation in insight tasks can be considered a "solution-related activation" (p. 1235) for problems that have not yet been solved. This idea would fit very well with the increased right OFC activation that we observed in incoherent triads and could give a hypothetical explanation for the differences in neural results between the simultaneous and the sequential presentation format: When the three triad words are presented simultaneously, similar associations between them may lead to an initial overlapping activation of semantic networks for each of the three concepts that may then trigger

the feeling of coherence, which, if strong enough, will result in the explicit retrieval of the common associate. If the spread of the activation does not lead to overlapping activation, no feeling of coherence may be induced and the triad may thus be judged as incoherent. In contrast, with a sequential presentation of the semantic concepts, an immediate overlapping of activation is prevented because the words are not presented at the same time. Particularly, the semantic network activated for each individual word has to be retained in memory in order to be integrated after the presentation of the last word. This integration process may be reflected by a solution-related activation in the right OFC in parallel with an activation of temporal regions that input the OFC with information from initial semantic processing steps. Additionally right frontal regions have been associated with working memory load (e.g., Petrides, Alivisatos, Meyer, & Evans, 1993; Rypma, Prabhakaran, Desmond, Glover, & Gabrieli, 1999), which would not only be higher in the sequential as compared to the simultaneous activation but also gradually increase during the attempt to find a solution. Both solution- and working memory-related activation would be expected to terminate at the point where a solution is found. Given that no solution is found in incoherent triads, it will therefore last longer for incoherence judgments than for coherence judgments. This may explain the overall increase of right OFC together with middle temporal gyrus activation shortly after all three triad words have been presented.

5. General discussion

The present experiments investigated intuitive coherence judgments in the semantic domain. Specifically, it was aimed to explore the neural basis of information processing toward a first implicit recognition of a link between semantic concepts. In both experiments, a semantic coherence judgment task was applied where participants had to indicate whether three words converged on a fourth remote associate (Bowers et al., 1990). During task performance, participants' brain activation was recorded via high temporal resolution MEG in order to disentangle the underlying neural dynamics of such coherence judgments and test to what extent the neural mechanisms are in accordance with the mechanisms proposed from findings on coherence judgments in the visual domain. In Experiment 1, the three words were presented all at the same time (simultaneously). Experiment 2 was similar to Experiment 1 except that the words were presented one at a time (sequentially). The two different formats of presentation were applied in order to investigate whether a simultaneous revelation of all information is necessary to initialize an intuitive feeling of coherence. Assuming an intuitive feeling of coherence to be achieved via an automatic spread of activation that leads to simultaneous activation of remotely related semantic concepts, crucial changes in processing strategies due to temporal dynamics of the presentation were predicted.

For intuitive coherence judgments with simultaneous presentation of information, specific processing mechanisms involving the orbitofrontal cortex as a global integrator have been suggested (e.g., Horr et al., 2014; Luu et al., 2010; Volz & Von Cramon, 2006), and those mechanisms are in accordance with the findings in our Experiment 1. Experiment 2 revealed similar behavioral results but striking neural activation differences. The brain seems to employ different mechanisms to deal with the two different presentation formats: When all information is available at one time (Experiment 1) a rapid response may be achieved via immediate integration and creation of a coarse representation in the left OFC (Experiment 1). On the other hand, when information is presented bit by bit (Experiment 2), initial integration is not possible due to insufficient (temporal) overlap of activated concepts. The three individual words may then have to be maintained in memory and reactivated at a later point for an attempt to achieve overlapping activation that leads to coherence perception. The right OFC may enable this process, which lasts longer, the longer it takes to reach activation overlap. This would be why we find increased right OFC activation for triads finally judged as incoherent.

Considering the striking differences in neural activation between a simultaneous and a sequential presentation, it is somewhat unexpected that the behavioral outcomes of both tasks were very similar. Though one must be careful drawing conclusion from cross-study comparisons, the present results do not hint at any significant difference between participants' performance and bias in Experiment 1 and 2. Even more crucially, participants' ability to judge the coherence of the word triads with or without giving a solution word does not seem to be impaired by a sequential presentation. Also, reaction times do not differ. This indicates that the same efficiency of coherence judgments, independent of an explicit solution, can be achieved via different neural strategies. When one thinks about the multiple ways in which information can be revealed in a realistic environment, it makes sense that the brain is able to flexibly adapt its processing strategies to cope equally well with the demands of quick, preliminary judgments in different situations. Especially the ability to integrate information that is presented at different points in time and use those as a basis for quick and flexible decision-making seems crucial for a successful interaction with the environment. On the basis of the present data, we propose that intuitive judgments for simultaneously presented semantic concepts are based on an automatic activation of associates that are immediately and in a Gestalt-like fashion integrated in the OFC. Sequential presentation requires maintaining and reuptake of concepts in memory as initial activation is not sufficiently overlapping. This proposal of course needs to be tested in further neural and behavioral studies specifically designed to disentangle such processing differences. While the present study was specifically interested in the initial feeling of coherence that supposedly emerges during the "guiding stage" (Bowers et al., 1990) of intuition, it may in future studies be interesting to differentiate between implicitly and explicitly coherent triads and investigate to which extend the proposal of an activation pattern gradually evolving from implicit to explicit coherence judgments hold for the different presentation formats.

The behavioral similarities and neural differences between Experiment 1 and Experiment 2 are especially interesting because they demonstrate that what–on a behavioral level–has been defined as intuitive judgments can be archived with

similar efficiency via very different neural strategies. The intuition index measures participants' ability to make adequate judgments on coherence (or incoherence) between pieces of information without an explicit recognition of the connecting concept this coherence is based on. It therefore appears to be inherently linked to a definition of intuition as the preliminary perception of coherence (Bowers et al., 1990) and the mechanistic explanation of intuitive coherence judgments being based on an automatic spread that leads to simultaneous activation of overlapping semantic concepts (Colin & Loftus, 1975). The present results however indicate that it may be more realistic and fruitful for future research to define intuition measured by the intuition index more broadly as "above-chance judgments [...] on the basis of information that is not consciously retrieved" (Bolte et al., 2003) and to keep in mind that there may be many strategies the brain can employ to arrive at an overlapping activation between concepts and thereby such above-chance judgments. Disentangling those strategies, determining the contexts in which they are applied and finding common core elements they are sharing will be major challenges in future research aimed at a deeper understanding of the neural underpinnings of intuitive coherence judgments and related conceptualizations of intuition.

Conflict of interest

The authors have no conflict of interest to declare.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2015.10.008.

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